ADVANCES IN BEAM TESTS OF DIELECTRIC BASED ACCELERATING STRUCTURES*

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Abstract

Diamond is being evaluated as a dielectric material for dielectric loaded accelerating structures. It has a very low microwave loss tangent, high thermal conductivity, and supports high RF breakdown fields. We report on progress in our recent beam tests of the diamond based accelerating structures of the Ka-band and THz frequency ranges. Wakefield breakdown test of a diamond-loaded accelerating structure has been carried out at the ANL/AWA accelerator. The high charge beam from the AWA linac (~70 nC, σ_z ~ 2 mm) was passed through a rectangular diamond loaded resonator and induce an intense wakefield. A groove is cut on the diamond to enhance the field. Electric fields up to 300 MV/m has been generated on the diamond surface to attempt to initiate breakdown. Wakefield effects in a 250 GHz planar diamond accelerating structure has been observed at BNL/ATF accelerator as well. We have directly measured the mm-wave wake fields induced by subpicosecond, intense relativistic electron bunches in a diamond loaded accelerating structure via the dielectric wake-field acceleration mechanism. A surface analysis of the diamond has been performed before and after the beam test.

INTRODUCTION

Diamond has been proposed as a dielectric material for dielectric loaded accelerating (DLA) structures [1-3]. Dielectric Loaded Accelerator structures using ceramics or other materials and excited by a high current electron beam or an external high frequency high power RF source have been under extensive study for many years [4-7]. Low loss microwave ceramics, fused silica, and CVD polycrystalline and single crystal diamonds [11] have been considered as materials for dielectric based accelerating structures to study of the physical limitations encountered in developing field strengths > 100 MV/m at microwave [4-6] and > GV/m at THz frequencies in a dielectric based wakefield accelerator [6,7,11,12]. THz radiation has been generated recently by a short ~10 GV/m pulse within a 100 µm diameter quartz fiber [7]. A planar diamond-based DLA structure was proposed recently by Omega-P, Inc., where the dielectric loading of this structure was to be made of diamond slabs fabricated using CVD (chemical vapor deposition) technology [2].

Our choice of CVD (Chemical Vapor Deposition) diamond as a loading material will allow demonstration of high accelerating gradients; up to 0.5-1.0 GV/m as long as the diamond surface can sustain a 0.5-1.0 GV/m short pulse (~ 10 ns) rf field without breaking down. Diamond has the lowest coefficient of thermal expansion, highest thermal conductivity (2×10^3 Wm^{-1} K^{-1}) and extremely low loss tangent ($<10^{-4}$) at Ka-W frequency bands. Secondary emission from the CVD diamond surface can be dramatically suppressed by diamond surface dehydrogenation or oxygen termination [3,6,8-12]. The CVD process technology is rapidly developing, making the CVD diamond fabrication process fast and inexpensive. Given these remarkable properties, diamond should find numerous applications in advanced accelerator technology [3]. Planar diamonds are available commercially in various grades including single crystal diamonds. The goal of this research is to perform a wakefield acceleration experiment using a diamond loaded structure and to test diamond for breakdown.

Euclid Techlabs had performed two wakefield experiments with diamond loaded accelerating structures: a 25 GHz structure at the Argonne Wakefield Accelerator of ANL and a 250 GHz structure at the Accelerator Test facility of BNL [9].

BEAM EXPERIMENTS WITH THE DIAMOND BASED DLA STRUCTURES

Significant progress has been made in the development and testing of high gradient dielectric accelerating structures (DLA) [1]. As various engineering challenges (breakdown, dielectric losses, efficient RF coupling) have been overcome, the technology of high gradient RF or wakefield driven dielectric loaded structures appears increasingly attractive as a viable option for high energy accelerators. Typical DLA considered in experiments is a cylindrical, dielectric tube with an axial vacuum channel inserted into a conductive sleeve or a rectangular waveguide loaded with planar dielectric pieces. In this paper we will focus on the latter structure. The dielectric constant, thickness of dielectric and the size of a vacuum gap are chosen to adjust the phase velocity of the fundamental mode at certain frequency to the beam velocity ~ c. In the application to particle acceleration, the dominant TM_{01} mode is of main interest.

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We report here the results of a wakefield breakdown test of single crystal diamond-loaded rectangular accelerating structure [10]. The high charge beam from the AWA linac (~70 nC, σ_z = 2 - 2.5 mm) was transported through a rectangular diamond - loaded resonator and induced an intense wakefield [12]. A deep (200 µm) and narrow (20 µm) groove is cut on the diamond surface to enhance the field (by approximately a factor of ε). Electric fields at least of 300 MV/m were present on the diamond surface in the groove (decay time ~ 35 ns). A surface analysis of the diamond was performed before and after the beam test. No breakdown-type damage was observed on scanning electron microscopy images [10].

Structure design was presented earlier in [10], Fig.1. Parameters of the structure were determined via parametric simulations with constraint on the thickness of commercially available diamond plates, and the minimal gap size was determined by beam dynamics [11].

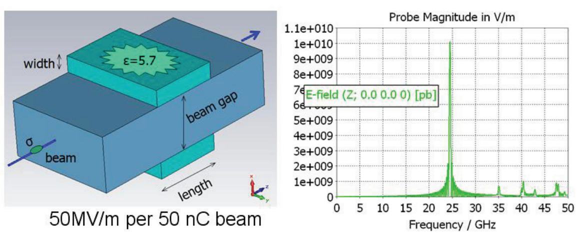

Figure 1: Left: geometry of the diamond resonator: length = 4mm, width = 1.2mm, beam gap = 4mm and overall width = 8mm. Right: spectrum of the wakefield (simulation).

To achieve stronger fields on the surface of the diamond two small 20 and 25 micron – wide, 220 micron deep grooves were laser cut on the diamond surface transverse to the beam propagation direction. There is a large field enhancement in these grooves: the field at the entrance to the groove is higher by a factor of ~ ε (5.7) than it would be in its absence [10] – a five time field enhancement because of the boundary conditions for the electric field at the surface of dielectric. For deep and narrow scratches (aspect ratio of 10 and higher) such enhancement is practically ε. As the groove becomes wider and shallower the field enhancement drops.

Diamond laser cutting is not a trivial procedure. Multistage cleaning was used to get rid of partial conductivity from carbon deposits. Special technology has been used that allowed removing practically all remaining carbon. SEM measurement confirmed that the laser cutting was successful as well as that target values of groove widths were achieved [11], Fig. 2.

In the experiment we manage to transport 72 nC charge through the structure, which corresponded to at least 300 MV/m on the surface of the groove. The bunch length measurement was not available, so for this estimate we used maximum value of 2.5mm. Shorter bunch length yields higher gradient.

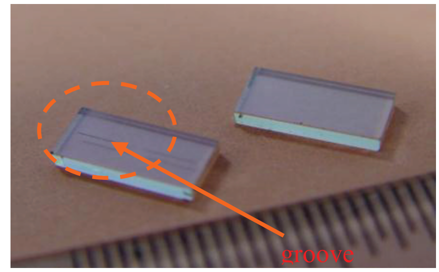

Figure 2: Field Enhancement groove machined in a planar diamond sample.

We used scanning electron microscopy to analyze the condition of the diamond surface before and after the experiment. Besides the presence of lint the surface did not undergo noticeable changes, Fig.3.

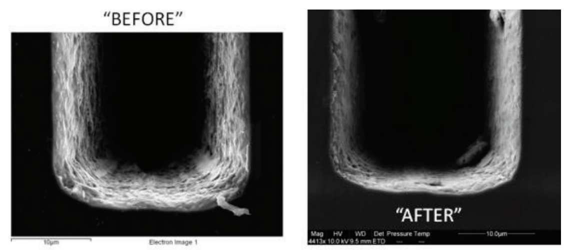

Figure 3: SEM measurement of the groove: right – before, left – after the test.

WAKEFIELD ACCELERATION IN A 250 GHZ DIAMOND STRUCTURE

Recently, we have directly measured THz wakefield acceleration/deceleration in a diamond loaded dielectric accelerating structure.

Proof of principle experiments at BNL/ATF [9] have studied wakefields in diamond structures in the 250 GHz regime. It should be noted especially that in this experiment diamond was for the first time used as a loading material for a wakefield dielectric based accelerating structure [9]. Fields produced by a leading (drive) beam were used to accelerate a trailing (witness) electron bunch, which followed the drive bunch at a variable distance. The energy gain of a witness bunch as a function of its separation from the drive bunch describes the time structure of the generated wakefield. By sweeping the separation between the drive beam and the witness beam and energy measurements of the witness beam a 0.25 THz frequency wakefield was directly sampled at the scale of about one wavelength [9,13].

The general experimental methodology is the following: a pair of beams is generated: - a high charge drive beam, followed by a smaller witness beam at a variable distance *d*. The drive beam generates a wake there and the witness beam is accelerated or decelerated depending on the delay between the two beams. We record the witness beam energy change, ΔE as a function of *d*.

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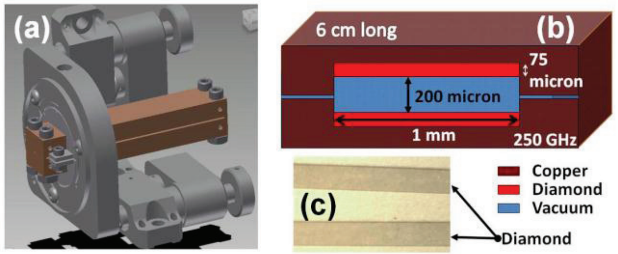

Figure 4: (a) 250 GHz structure mounted on a positioning holder; b) structure dimensions; c) photo of diamond after the experiment exhibiting no visible damage.

In the experiment we used 75 micron thick polycrystalline diamond plates loaded in a 6 cm long waveguide, Fig.4. The beam gap was 200 microns. This structure yields a wakefield dominated by a TM_{11} – like mode with 1200 micron wavelength (0.25 THz). The ATF drive beam is very short and also excites higher order modes, hence the wake is not a pure sine wave [9].

The subpicosecond drive and witness beams are produced by the technique described in [9]. A beam accelerated off-crest hence having a linear energy chirp (the head of the beam having lower energy than the tail) passes through a a dispersionless translating section. A mask is placed between the dogleg dipoles where the beam transverse size is dominated by the correlated energy spread. After the second dipole magnet the transverse pattern introduced by the mask becomes the longitudinal charge density distribution. In our case the mask was motorized and allowed creation of a drive beam followed by a witness beam at a variable delay [9].

Calibration is done via coherent transition radiation (CTR) interferometry. We fitted the recorded transverse profile by a gaussian distribution with $\sigma_x = 50$ µm, $\sigma_y = 350$ µm. The longitudinal wakefield produced by a beam with this current distribution was numerically calculated and compared with the experimental results.

The relative change in witness beam energy depending on the drive – witness separation is measured on the spectrometer. Compared to the beam energy, when it does not go through the structure, we observe energy gain and loss in the interval from -0.6 to +0.65 MeV for the witness beam following a drive beam through the DLA structure. This yields a 10.8 MV/m gradient for a 6 cm structure. The measurement accuracy was limited by the spectrometer resolution ($\sigma = 0.028$ MeV), estimated using the sharpest features obtained on the spectrometer by measuring the FWHM (full width half maximum) and dividing it by 2.355 to obtain the equivalent Gaussian width. Fig. 5 shows the measured energy change (diamonds) as a function of drive – witness separation with error bars. The shape of the experimentally mapped wake (diamonds) agrees well with the theoretical (scaled) prediction (circles) based on the wakefield (solid line) calculated for the drive beam current distribution (dashed line).

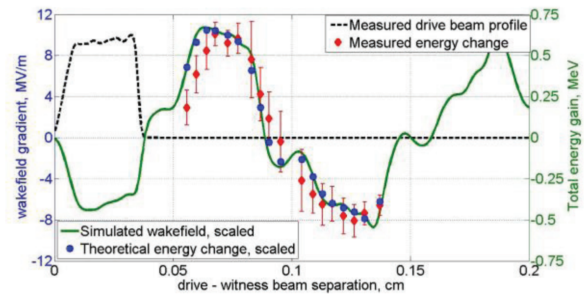

Figure 5: Energy gain of the witness beam as a function of separation from the drive beam.

SUMMARY

The emphasis of this paper is to present progress on development and fabrication of new types of diamond waveguides to be used for high gradient dielectric accelerating structures. We reported the results from development of a diamond DLA of GHz frequency range and wakefield tests of diamond-loaded rectangular accelerating structures at THz frequencies. We have directly measured THz wakefield acceleration and deceleration in a diamond loaded dielectric accelerating structure in an experiment where diamond was used for the first time in a wakefield dielectric based accelerating structure. In the 25 GHz frequency range, we achieved field levels on the order of 300 MV/m (35 ns pulse) in the structure using the 72 nC, 15 MeV beam at the Argonne Wakefield Accelerator Facility. Single crystal diamond plates produced by chemical vapor deposition (CVD) were used in the structure. A surface analysis of the diamond has been performed before and after the beam tests.

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